Workbench for vulnerability analysis of Vietnam energy sector

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Abstract. The paper addresses the problem of supporting research of the Vietnam energy sector vulnerability. The vulnerability study is understood as search for system weak points. A mathematical model has been developed to describe the energy sector of Vietnam. The model takes into account the characteristics and constraints of all objects of the energy sector: suppliers, consumers and the transport system. To study the vulnerability of the energy sector and make decisions, we have created a workbench that allows simulating increased loads and calculating the consequences. Specification-based database application development technology was applied to create the workbench. This technology allows you to quickly develop applications that provide interaction with databases and digital maps, as well as support interaction with external software modules. The main advantage of the proposed workbench is its flexibility and applicability at all stages of the study of the Vietnam energy sector vulnerability starting from gathering the energy operation and development information and ending with evaluation of satisfying demand in energy.

Keywords: Decision Support System, Vulnerability Analysis, Energy Sector, Specification.

1 Introduction

The resilience of an energy system can be understood as the system ability to prevent damage before disturbance events, mitigate losses during the events, and improve the recovery capability after the events [1]. The interdependent national energy system are united to form a country energy sector.

The main stages of the interdependent energy systems resilience research scheme are presented in [2]. The central role in the resilience research plays the vulnerability analysis [3]. The vulnerability characterizes the scale of negative system consequences caused by a disturbance impact on interdependent energy systems.

The vulnerability analysis process consists of the following general stages:

1. gathering an energy sector operation and development information
2. calculation on an energy sector model
3. solution data processing
4. solution data presentation
5. evaluation of satisfying demands

A workbench presented in this paper supports the vulnerability analysis of Vietnam energy sector and automates the stages from 2 to 5.

2 Related work

Decision support systems have a critical role in assessing the natural disasters risk of energy systems networks and in enabling their managers to test the effectiveness of alternative mitigation strategies and investments on resilience [4]. For example, CIP-Cast decision support system can predict scenarios of punctual damages to the different critical infrastructure components and impact scenarios, where services outages induced by the physical damage to critical infrastructure components, are assessed at different scales [5]. CIPCast was as a combination of free/open source software environments including Geographic Information System (GIS) [6].

A GIS technology play a major role in the construction of such decision support systems [7-9] because multi-source data and GIS-integrated analysis can contribute to a better disturbance prediction and mitigation planning [10, 11].

3 Methodology

The workbench represents ways of energy sector development as a directed graph (see Fig. 1). The first moment is always equal 0 and presents the current year. Each node of the graph represents the energy sector state at specific moment (year) in the future. Each arc defines a transition from state at one moment in time (year) to another state at next moment in time (year).

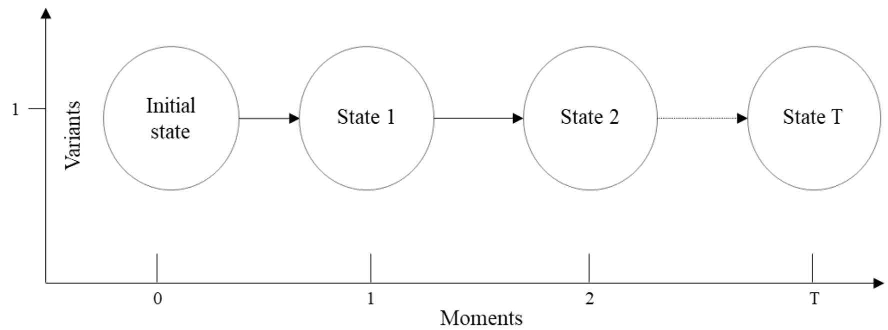


Fig. 1. An energy sector development scenario

Each node of the energy sector development graph is associated with the following information about the energy sector:

- demands in energy;
- energy transmission capacity and cost;
- energy production capacity and cost;
- energy transformation capacity and cost.

Thus energy sector development scenario is described as sequence of nodes at different time moments:

Node 0 — the energy sector model data for initial time moment
Node 1 — the energy sector model data for second time moment
Node 2 — the energy sector model data for third time moment
Node 3 and further — energy sector model data for next time moment

3.1 General view of energy sector balance model

The Vietnam energy sector model is based on the initial information of one of the national energy sector perspective development plans. Analysis of such options by means of the energy sector model can address the following specific strategic challenges of Vietnam energy sector development:

- the deployment of new energy sources of different kinds around the country, including nuclear power plants;
- the deployment of energy resources import entries on the area of the country;
- the order of the creation of new facilities of coal mining, natural gas extraction, crude oil extraction and refining taking into account the capabilities of existing and new energy resources transmission lines, etc.

A general energy sector model consists from the following equations and inequalities:

$$(\mathrm{C},\mathrm{X}) + (r,\mathrm{g}) \rightarrow min \tag{1}$$

$$\mathrm{AX} - Y = 0 \tag{2}$$

$$0 \leq X \leq D \tag{3}$$

$$0 \leq Y \leq R \tag{4}$$

where

X – the decision vector of the energy resources production, extraction, generation, transformation or transmission facilities usage;

Y – the decision vector of energy resources consumption;

A – the matrix of technological coefficients (rates) of energy resources production, extraction, generation, transformation or transmission facilities;

D – the vector of energy resources supply and transmission facilities capacity;

R – the vector of energy resources demand;

The first part of the goal function represents total costs of the FEC operation. The C is the cost vector of the energy resources production and transmission facilities.

The second part of the goal function characterizes financial losses due to energy resource shortages. The vector g is equal to the difference $(R - Y)$. The r is cost vector of energy resource shortages. The estimation of real costs of damage from a shortage is difficult due to variety of shortage after-effects, which are not always possible to identify and quantify.

3.2 The energy sector state visualization

There is a one digital map per each energy recourse distribution net. Each digital map should consists of 3 layers:

1. Consumers as polygon type layer;
2. Producers as point type layer;
3. Transmission links as line type layer.

To show state by color coloring rules for each layer type were created. Coloring rules for consumers are shown in Table 1.

Table 1. Coloring rules for consumers

Rule name	Consumption ratio interval in percents	Color	Description
No data	[-1, 0.0]	Cyan	Object is with undefined demand
Zero demand	[0.0, 0.2]	Light green	Consumer is with zero demand
Nondelivery	(0.2, 99.8)	Yellow	Consumer needs are not satisfied
Satisfied	[99.8, 100]	Green	Consumer needs are fully satisfied

Coloring rules for producers are shown in Table 2.

Table 2. Coloring rules for producers

Rule name	Production and up value of capacity ratio interval in percents	Color	Description
Not used	[0.0, 0.2]	Blue	Producer is not used at all
Normal	(0.2, 99.8)	Black	Normal usage
No reserve	[99.8, 100]	Green	Producer is fully loaded and do not have capacity reserve

Coloring rules for transmission links are shown in 3.

Table 3. Coloring rules for transmission links

Rule name	Transmission and up value of capacity ratio interval in percents	Color	Description
Not used	[0.0, 0.2]	Blue	Transmission link is not used at all
Normal	(0.2, 99.8)	Black	Normal usage
No reserve	[99.8, 100]	Green	Transmission link is fully loaded and do not have capacity reserve

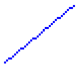
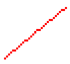
Colors of energy resource producer according to 1 are shown in 4.

Table 4. Colors of energy resource producer

Energy resource producer state	Rule name	Description
	Not used	Producer is not used at all
	Normal	Normal usage
	No reserve	Producer is fully loaded and do not have capacity reserve

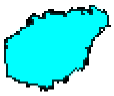
Colors of energy resource transmission link according to 2 are shown in 5.

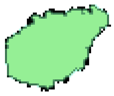
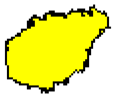
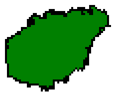
Table 5. Colors of energy resource transmission link

Energy resource transmission link state	Rule name	Description
	Not used	Transmission link is not used at all
	Normal	Normal usage
	No reserve	Transmission link is fully loaded and do not have capacity reserve

Colors of energy resource consumer according to Table 3 are shown in table 6.

Table 6. Colors of energy resource consumer

Energy resource consumer state	Rule name	Description
	No data	Consumer has undefined demand

	Zero demand	Consumer has zero value demand
	Nondelivery	Consumer needs are not satisfied
	Satisfied	Consumer needs are fully satisfied

4 Vietnam energy sector model

4.1 Assumptions

The energy sector model describes the following major energy systems of Vietnam:

- Gas supply system consists of natural gas fields which are combined into gas-producing areas and possible entries of imported liquefied natural gas. Natural gas transport within the country is represented by network of existing and new gas pipelines.
- Coal supply system. Coal mines can be aggregated by locality. The qualitative structure of coals can be taken into account by separation of particular kinds. Transport of coal between regions matches directions of the main cargo transfer paths.
- The crude oil refinery products supply system can be represented by the production and distribution of light oil and fuel oil. Transportation of petroleum products is represented by set roads, marine links and railways between producers and consumers.
- Power system. Power plants are divided into several types: thermal, hydro, nuclear power plants and renewable energy sources. Thermal power plants are classified by type of main fuel: natural gas, coal and fuel oil. Renewable energy source are divided into the solar cells, wind farms and thermal power plants using biomass.

Except for the production and transportation blocks in the energy sector model there is a block of consumption, which is represented by the main consumers of the energy sector, ranked by category of importance.

4.2 Nomenclature

The main symbols used in this paper are described below for quick reference.

Indices

R – amount of regions
p, r $\in \{1, R\}$ – order number of region
$l \in$ {a,b,g,z,e,o,u,h,d,k,w} – energy resource, where
a – anthracite;
b – brown coal;
g – natural gas;
z – LPG;
e – electricity;
o – crude oil;
u – gasoline;
h – FO;
d – DO;
k – kerosene;
w – aviation gasoline;

Input parameters

$\bar{Q}_r^l$ – up value of capacity to produce or extract energy resource l in region r, $l \in$a,b,g,z,o,u,h,d,k,w

$\bar{x}_{\mathrm{rp}}^l$ – up value of capacity to transmit energy resource l from region r to region p, $l \in$ {a,b,g,e,z,o,u,h,d,k,w}

$\bar{e}_{\mathrm{rp}}^l$ – up value of capacity to export energy resource l from region r to region p, $l \in$ {a,b,g,e,z,o,u,h,d,k,w}

$\overline{D}_r^l$ – up value of energy resource l demand in region r, $l \in$ {e,z,o,u,k,w}

$\bar{S}_r^{\mathrm{TPS,l}}$ – up value of total capacity of TPS burning fuel l in region r, $l \in$ {a,b,g,h,d}

v_r^l – value of burning fuel l to generate one unit of electricity on TPS in region r, $l \in$ {a,b,g,h,d}

$\bar{S}_r^{\mathrm{NPP}}$ – up value of total nuclear power plants (NPP) capacity in region r

$\bar{S}_r^{\mathrm{HPS}}$ – up value of total hydro power stations (HPS) capacity in region r

$\bar{S}_r^{\mathrm{oth}}$ – up value of others sources total capacity in region r

$y_r^l = \frac{\bar{Q}_r^l}{\overline{D}_r^o}$ – crude oil refinery coefficient for energy resource l production in region r, $l \in$ {h,d,k,w,z}

Output parameters

Q_r^l – energy resource l production in region r, $l \in$ {a,b,g,z,o,u,h,d,k,w}

x_{rp}^l – transport of energy resource l from region r to region p, $l \in$ {a,b,g,z,e,o,u,h,d,k,w}

e_{rp}^l – export of energy resource l from region r to region p, $l \in$ {a,b,g,z,e,o,u,h,d,k,w}

D_r^l – energy resource l consumption in region r, $l \in$ {e,z,o,u,k,w}

$S_r^{\mathrm{TPS,l}}$ – power generation by TPS burning fuel l in region r, $l \in$ {a,b,g,h,d}

S_r^{NPP} – power generation by NPP in region r

S_r^{HPS} – power generation by HPS in region r

S_r^{oth} – power generation by other sources in region r

Cost

$c_{Q_r^l}$ – cost of energy resource l produced in region r, $l \in$ {a,b,g,z,o,u,h,d,k,w}

$c_{S_r^{\text{TPS,l}}}$ – cost of power generated by TPS burning fuel l in region r, $l \in$ {a,b,g,h,d}

$c_{S_r^{\text{HPS}}}$ – cost of power generated by HPS in region r

$c_{S_r^{\text{NPP}}}$ – cost of power generated by NPP in region r

$c_{S_r^{\text{oth}}}$ – cost of power generated by other sources in region r

$c_{x_{\text{rp}}^l}$ – cost of one unit of energy resource l transmission (transportation or import) from region r to region p, $l \in$ {a,b,g,z,e,o,u,h,d,k,w}

$c_{e_{\text{rp}}^l}$ – losses due to one unit of exported energy resource l non-delivery from region r to region p, $l \in$ {a,b,g,z,e,o,u,h,d,k,w}

$c_{D_r^l}$ – losses due to one unit of energy resource l non-delivery for consumption in region r, $l \in$ {a,b,g,z,e,o,u,h,d,k,w}

4.3 Generalized Network Flow Model Mathematical Formulation

Energy resource balance

Natural gas balance in region r

$$\text{Q}_r^g + \sum_{p\neq r} x_{\text{pr}}^g - \sum_{p\neq r} x_{\text{rp}}^g - \sum_{p\neq r} e_{\text{rp}}^g - v_r^g \text{S}_r^{\text{TPS,g}} \text{-D}_r^{\text{g}} \geq 0 \quad (5)$$

Anthracite balance in region r

$$\text{Q}_r^a + \sum_{p\neq r} x_{\text{pr}}^a - \sum_{p\neq r} x_{\text{rp}}^a - \sum_{p\neq r} e_{\text{rp}}^a - v_r^a \text{S}_r^{\text{TPS,a}} \text{-D}_r^{\text{a}} \geq 0 \quad (6)$$

Brown coal balance in region r

$$\text{Q}_r^b + \sum_{p\neq r} x_{\text{pr}}^b - \sum_{p\neq r} x_{\text{rp}}^b - \sum_{p\neq r} e_{\text{rp}}^b - v_r^b \text{S}_r^{\text{TPS,b}} \text{-D}_r^{\text{b}} \geq 0 \quad (7)$$

Crude oil balance in region r

$$\text{Q}_r^o + \sum_{p\neq r} x_{\text{pr}}^o - \sum_{p\neq r} x_{\text{rp}}^o - \sum_{p\neq r} e_{\text{rp}}^o - D_r^o \geq 0 \quad (8)$$

LPG balance in region r

$$Q_r^z + y_r^z D_r^o + \sum_{p\neq r} x_{\text{pr}}^z - \sum_{p\neq r} x_{\text{rp}}^z - \sum_{p\neq r} e_{\text{rp}}^z \text{-D}_r^z \geq 0 \quad (9)$$

FO balance in region r

$$\text{Q}_r^h + y_r^h D_r^o + \sum_{p\neq r} x_{\text{pr}}^h - \sum_{p\neq r} x_{\text{rp}}^h - \sum_{p\neq r} e_{\text{rp}}^h - v_r^o S_r^{\text{TPS,h}} - D_r^{\text{h}} \geq 0 \quad (10)$$

DO balance in region r

$$\text{Q}_r^d + y_r^d D_r^o + \sum_{p\neq r} x_{\text{pr}}^d - \sum_{p\neq r} x_{\text{rp}}^d - \sum_{p\neq r} e_{\text{rp}}^d - v_r^d S_r^{\text{TPS,d}} - D_r^{\text{d}} \geq 0 \quad (11)$$

Gasoline balance in region r

$$\text{Q}_r^u + y_r^u D_r^o + \sum_{p\neq r} x_{\text{pr}}^u - \sum_{p\neq r} x_{\text{rp}}^u - \sum_{p\neq r} e_{\text{rp}}^u \text{-D}_r^u \geq 0 \quad (12)$$

Kerosene balance in region r

$$\text{Q}_r^k + y_r^k D_r^o + \sum_{p\neq r} x_{\text{pr}}^k - \sum_{p\neq r} x_{\text{rp}}^k - \sum_{p\neq r} e_{\text{rp}}^k \text{-D}_r^k \geq 0 \quad (13)$$

Aviation gasoline balance in region r

$$\text{Q}_r^z + y_r^z D_r^o + \sum_{p\neq r} x_{\text{pr}}^z - \sum_{p\neq r} x_{\text{rp}}^z - \sum_{p\neq r} e_{\text{rp}}^z \text{-D}_r^z \geq 0 \quad (14)$$

Electricity balance in region r

$$\sum_l S_r^{\text{TPS,l}} + \text{S}_r^{\text{HPP}} + \text{S}_r^{\text{HPS}} + S_r^{\text{oth}} + \sum_{p\neq r} x_{\text{pr}}^e - \sum_{p\neq r} x_{\text{rp}}^e - \sum_{p\neq r} e_{\text{rp}}^e - D_r^e \geq 0,$$

$$l \in \{a,b,g,h,d\} \tag{15}$$

Bound constraints

Up values of energy resource l production in region r

$$0 \le Q_r^l \le \bar{Q}_r^l,\ l \in \{a,b,g,z,o,u,h,d,k,w\} \tag{16}$$

Up values of power generation by TPS burning fuel l in region r, $l \in \{a,b,g,h,d\}$

$$0 \le S_r^{\mathrm{TPS,l}} \le \bar{S}_r^{\mathrm{TPS,l}} \tag{17}$$

Up values of NPP power generation in region r

$$0 \le S_r^{\mathrm{NPP}} \le \bar{S}_r^{\mathrm{NPP}} \tag{18}$$

Up values of HPS power generation in region r

$$0 \le S_r^{\mathrm{HPS}} \le \bar{S}_r^{\mathrm{HPS}} \tag{19}$$

Up values of power generation by other sources in region r

$$0 \le S_r^{\mathrm{oth}} \le \bar{S}_r^{\mathrm{oth}} \tag{20}$$

Up values of energy resource l transport between region r and p

$$0 \le x_{\mathrm{rp}}^l \le \bar{x}_{\mathrm{rp}}^l,\ l \in \{a,b,g,e,z,o,u,h,d,k,w\} \tag{21}$$

Up values of energy resource l export between region r and p

$$0 \le e_{\mathrm{rp}}^l \le \bar{e}_{\mathrm{rp}}^l,\ l \in \{a,b,g,e,z,o,u,h,d,k,w\} \tag{22}$$

Up values of consumption of energy resource l in region r

$$0 \le D_r^l \le \overline{D}_r^l,\ l \in \{e,z,u,k,w\} \tag{23}$$

4.4 Goal function

$$\sum_r [\sum_{\mathrm{l=\{a,b,g,z,o,u,h,d,k,w\}}} c_{Q_r^l} Q_r^l + \mathrm{GEN}_r + \sum_{r \ne p} \sum_{\mathrm{l=\{a,b,g,e,z,o,u,h,d,k,w\}}} c_{x_{\mathrm{rp}}^l} x_{\mathrm{rp}}^l + \mathrm{EXPORT}_r + \mathrm{LOSS}_r] \tag{24}$$

$$\mathrm{GEN}_r = \sum_{\mathrm{l=\{a,b,g,h,d\}}} c_{S_r^{\mathrm{TPS,l}}} S_r^{\mathrm{TPS,l}} + c_{S_r^{\mathrm{NPP}}} S_r^{\mathrm{NPP}} + c_{S_r^{\mathrm{HPS}}} S_r^{\mathrm{HPS}} + c_{S_r^{\mathrm{oth}}} S_r^{\mathrm{oth}} \tag{25}$$

$$\mathrm{EXPORT}_r = \sum_{r \ne p} \sum_{\mathrm{l=\{a,b,g,e,z,o,u,h,d,k,w\}}} c_{e_{\mathrm{rp}}^l} e_{\mathrm{rp}}^l \tag{26}$$

$$\mathrm{LOSS}_r = \sum_{\mathrm{l=\{a,b,g,e,z,o,u,h,d,k,w\}}} c_{D_r^l} \left(\overline{D}_r^l - D_r^l\right) \tag{27}$$

To find minimum of goal function (24) is to find costs minimum. Equation (25) is total power generation of region r. Equation (26) is total region r losses due to energy resources non-delivery outside country. Equation (27) is total region r losses due to energy resources non-delivery inside country.

5 Workbench for vulnerability analysis of Vietnam energy sector

For vulnerability study of energy sector, an expert needs to be able to interact with source data of the energy sector model, prepare data for calculations, configure and execute calculations, and view results. Energy sector model objects are represented as relational database entities. Therefore, database interaction is one of base functions of the information system for studying the vulnerability of the energy sector.

Information systems that provide the implementation of CRUD (create, read, update, delete), search and some other operations (for example, reports generation) are called database applications. Database application development is a routine and time-consuming process because you have to perform many repetitive steps. Indeed, the code parts, which implement the typical operations for different tables usually have no substantial differences, besides from the names of the used tables and fields. There are approaches to partially automate the development of database applications. For example, using the Hibernate / NHibernate [12], Entity Framework [13] libraries allows you to automate the building of the object model of database tables. However, instead of interacting with tables, the application interacts with objects. In any case, the rest of the application code still needs to be written.

Also, a model-oriented approach is used for automate the development of database applications. For example, "Model-Based User Interface Development" [14] or "Model Driven Architecture" [15]. The formal representation of information about AIS structure is used to generate database objects and the code of client application. The generated code is very schematic and requires further development to make it of production quality. As a result it becomes very hard to reflect the changes in the specification, which usually happen during the application life-cycle.

We used an approach based on the use of specifications of database applications (SDA) [16, 17] to create a system for vulnerability study of the energy sector. SDA is a declarative representation of a database application model. SDA contains the minimum information required in a pure form about database tables, their fields, relationships between them and their use in the database application. All the other tasks are performed by general algorithms, controlled by SDA. In addition, in the SDA, you can configure the call of external subsystems and the references of database tables with objects of digital maps. To create the SDA, we used the GeoARM tool, which provides an interactive setup of all the necessary database objects. Interpreting SDA GeoARM becomes an applied information system that provides a user interface for interacting with a database, building user queries, calling external subsystems and interacting with digital maps.

The Workbench for vulnerability analysis of energy sector (see Fig. 2) created with the help of GeoARM provides interaction with the entities of the ES database in the modes of tables and individual records, and also allows you to build user queries and display information on digital maps. Researcher can generate map objects if there are fields in the database with the coordinates of the objects. You can also display on the map the result of a user query to the database. In this case, you can set the color of objects on the map depending on the values of a specific field of the query result. We can run compute modules that return results to the database. Further, based on the results obtained, we can create digital map objects and carry out analysis. In addition, you can display the result of a custom query to the database on the map. At the same time, you can set the color of objects on the map depending on the values of a specific characteristic of objects in the energy sector.

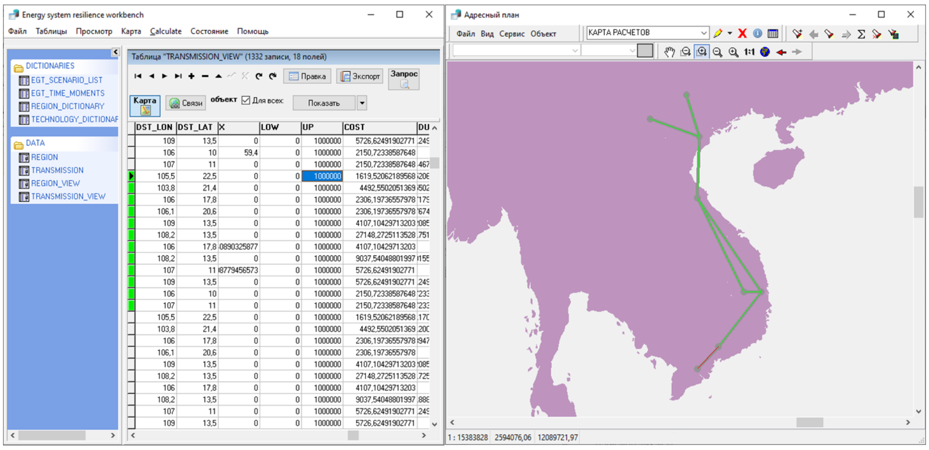


Fig. 2. Workbench for vulnerability analysis of energy sector

6 Calculation Module

A special tool has been developed to provide calculation on the model (5)-(27). The calculation module reads the Vietnam energy sector operation and development information from database and arranges that data into a development scenario (Fig 1). Then the module transforms the particular data associated with each node of directed graph shown in Fig. 1 into the linear programming problem (5)-(27) and solves the constructed problems sequentially. Thus the module can help to analyze time series of different energy sector parameters.

7 Conclusions

In the paper, we considered the problems concerned supporting the research of the Vietnam energy sector vulnerability. Conducting vulnerability studies requires a lot of efforts to prepare data, process data, perform calculations and analyze the results. The vulnerability analysis support requires user-friendly software that allows one to process data, run calculation modules, analyze and display the results.

We have developed a workbench to support the vulnerability analysis of interdependent national energy systems. The workbench is based on structural specifications that allow standardized solutions to the wide range of problems. The developed workbench allows us to solve the following tasks:

- Interact with the database through a convenient user interface,
- Execute external calculation modules,
- Conduct data analysis: build queries to the database, build thematic maps in the GIS.

An example of the workbench to support finding the Vietnam energy sector vulnerability analysis was considered. It is shown that the described tools provides the flexible prototyping and fast implementation of applications. And in comparison with other approaches, the main advantage of proposed workbench is that it is applicable for all stages of the vulnerability analysis starting from gathering the energy operation and development information and ending with evaluation of satisfying demand in energy.

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